Tunnel junction transistor laser

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A transistor laser with a tunnel junction collector is demonstrated. Its optical output is sensitive to third terminal voltage control owing to the electron tunneling (photon-assisted or not assisted) from the base to collector, which acts in further support of resupply of holes for recombination in addition to the usual base Ohmic current, I_B. Collector tunneling enhances laser operation even under a weak collector junction field and quenches it under a strong reverse-biased field. The sensitivity of the tunnel junction transistor laser to voltage control enables the tunnel junction transistor laser to be directly modulated by both current and voltage control. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3077020]

Fundamental to the transistor is the base and base current. This is evident at once from the original transistor of Bardeen and Brattain,[1] the point contact transistor with only, and uniquely, the base region semiconductor material. The base current (I_B) separates the low impedance input, the minority "emitter" current (I_E), from the high impedance output, the "collector" current (I_C), thus yielding a "transfer resistor" ($I_E+I_B+I_C=0$, $\beta=\text{gain}=|I_C/I_B|$, $\beta \geq 10$, $I_E>I_C,I_B>0$). If now, over 60 years later, we consider the highest speed transistor,[2] the *n*-*p*-*n* heterojunction bipolar transistor (HBT), which operates at small size and high current density, there is enough base current (and recombination) in a small enough volume, say, of "good" geometry, to change spontaneous recombination into stimulated recombination. This can be the basis of a transistor laser (TL),[3] particularly if quantum wells are inserted into the base region to control the recombination (trading-off electrical gain β for optical gain) and if, moreover, the base region, a resonator, is afforded adequate Q. As shown elsewhere,[4] the recombination optical signal, via internal Franz–Keldysh (FK) absorption,[5] causes voltage-dependent breakdown and negative resistance in the TL collector characteristics.[6] In the present work we show that high p^+ and n^+ tunnel-junction doping can be employed at the collector to enable the laser operation to be more effectively controlled by changes in bias (voltage), which makes possible a direct (circuit) scheme of voltage modulation in addition to the usual one of current modulation. This is particularly advantageous in signal processing. The collector tunnel junction (TJ) is an additional source of hole resupply to the base, and to recombination, complementing and competing with the usual base current I_B. We show that the collector TJ leads to a sensitive region, a voltage-dependent "sweet spot," in the laser operation. We show that a TJ can be used to enhance TL operation, and simultaneously it can be quenched by photon-assisted (FK) tunneling, thus adding significantly to TL flexibility and use.

The *n*-InGaP/p^+-GaAs/n^+-GaAs TJ HBT layer structure of the present work, and a comparison *n*-InGaP/p^+-GaAs/n^--GaAs HBT structure without a collector TJ are grown by metal-organic chemical-vapor deposition. The TJ HBT structure consists of a 40 nm $In_{0.49}Ga_{0.51}P$ emitter Si-doped to 3×10^{17} cm^{-3}, an 85 nm GaAs base C-doped to 1×10^{19} cm^{-3}, a single undoped 15 nm $In_{0.15}Ga_{0.85}As$ base-region quantum well at wavelength $\lambda\approx980$ nm, and a 40 nm GaAs collector Si-doped to 7×10^{18} cm^{-3}. The comparison HBT-TL structure is essentially identical to the TJ HBT structure except its collector is a 60 nm GaAs layer Si-doped to 2×10^{16} cm^{-3}. The devices are fabricated as described in Refs. 7 and 8. The cleave-to-cleave emitter-base cavity length is 400 μm.

Figure 1 shows the schematic band diagram of the TJ-TL with all the key physical processes labeled. I_E is the emitter current (minority current in the base) with the junction in forward bias, I_B is the resupply of holes by the usual base Ohmic contact, I_{fkT} is the resupply of holes by the FK photon-assisted tunneling, I_{rT} represents the resupply of holes via the direct tunneling of electrons, and I_t is the usual minority carrier current of injected electrons that do not recombine in the base and are collected. The collector current I_C consists of the usual transport component across the base I_t, the FK portion I_{fkT}, and the direct TJ current I_{rT} or

$$I_C = I_t + I_{rT} + I_{fkT}. \tag{1}$$

The base recombination current I_{Br} is expressed as the sum of the hole components or

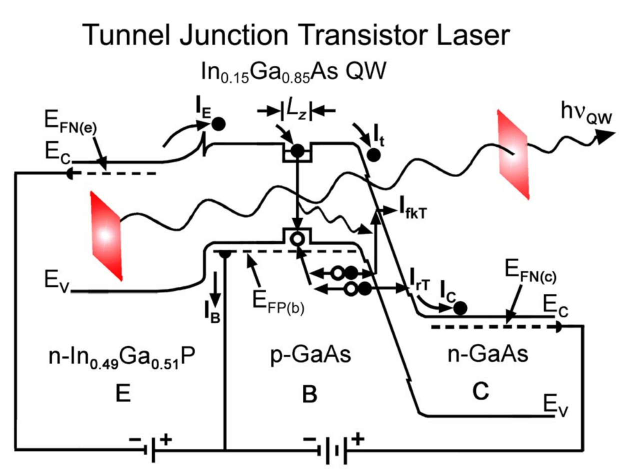

FIG. 1. (Color online) Schematic band diagram of a TJ-TL shown with a generic resonator cavity.

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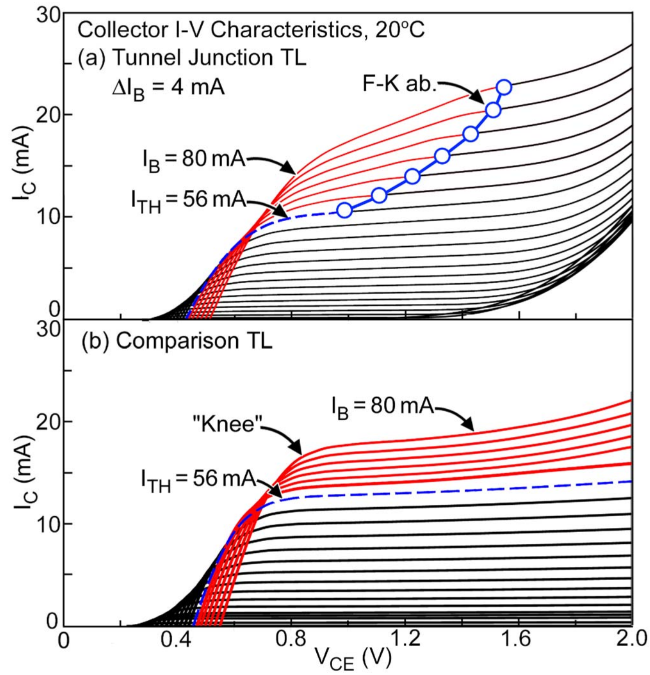

FIG. 2. (Color online) The collector *I-V* characteristics of (a) a TJ-TL and (b) a comparison TL without a collector TJ. Below the "knee" voltages, the transistors are biased in saturation. The tunneling process is evident from the slope of the TJ-TL collector current I_C vs emitter-collector voltage bias, V_{CE} (0.4–1.6 V), which otherwise would be "flat" as for the collector *I-V* of the comparison TL.

$$I_{\mathrm{Br}} = I_B + I_{\mathrm{fk}T} + I_{rT}. \tag{2}$$

Figure 2 shows the collector *I-V* characteristics of (a) the TJ-TL and (b) the comparison TL of lesser collector doping and no TJ. The forward-active mode of the TJ-TL operation (i.e., the base-collector junction in reverse bias) is indicated by the collector current I_C being nearly constant (i.e., "flat") despite further increase in V_{CE} above the "knee" voltages of 0.4 V (I_B=56 mA) to 0.8 V (I_B=80 mA). The effects of collector tunneling [Fig. 2(a)] are evident from the upward slope in the collector current, I_C versus V_{CE}, that otherwise would be relatively "flat" [see, Fig. 2(b) for comparison]. In the comparison TL, collector tunneling is negligible; hence, $I_C \approx I_t$ (usual collector current). However, in the TJ-TL, I_C increases as a function of V_{CE} owing to the various tunneling components [Eq. (1)]. In the presence of a stimulated-emission optical field and laser operation of the TJ-TL, the tunneling process occurs predominantly via FK (photon-assisted) absorption ($I_C \approx I_t + I_{\mathrm{fk}T}$). Direct tunneling (not photon-assisted) can be observed at higher V_{CE} biases ($I_C = I_t + I_{\mathrm{fk}T} + I_{rT}$).

The collector *I-V* characteristics of the TJ-TL agree in form well with its optical output, with the *LI-V* characteristics shown in Fig. 3. In the operation of the TJ-TL under weak collector junction field (left region 1 of Fig. 3), collector tunneling (photon-assisted, $I_{\mathrm{fk}T} > 0$) enables the efficient supply of holes to the quantum-well active region, and thus, improves the laser optical output by two times that of the comparison TL. We note that the holes supplied by collector tunneling need only relax a distance of ~30 nm (from collector to the base quantum well), as opposed to the lateral distance of 5 μm traversed by holes supplied by the base Ohmic contact (I_B). The photon absorption resulting from the weak collector junction field is not sufficient to overcome the photon gain established by emitter and base carrier injection ($I_E, I_B > 0$). However, under stronger reverse-biased collector junction field (region 2 of Fig. 3), optical output is reduced and subsequently quenched by FK absorption. The collector TJ, thus, enables the laser output to be controlled effectively by the use of a third terminal control voltage. Despite relying on only the bulk FK effect, the proximity of the collector TJ to the photon generation center (QW), and the strong coupling of the tunneling process to the cavity optical field, makes possible an effective direct voltage modulation mechanism. This enables the TJ-TL to be directly modulated via a current ($\delta I_E, \delta I_B$) as well as by voltage control ($\delta V_{\mathrm{CE}}, \delta V_{\mathrm{BC}}$).

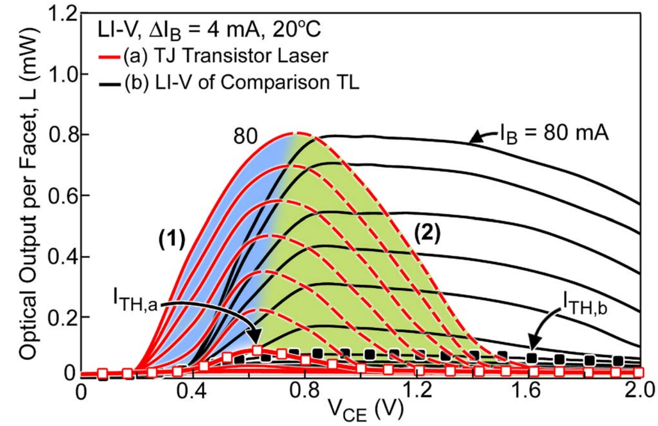

FIG. 3. (Color online) The dependence of optical output of the TJ-TL (Figs. 1 and 2) on V_{CE}, indicating the enhancement ($V_{\mathrm{CE}} < 0.8$ V) and quenching ($V_{\mathrm{CE}} \geq 0.8$ V) of the laser output by FK photon-assisted tunneling (photon absorption). The *LI-V* of the comparison TL (b) shows similar behavior occurring gradually except at higher $V_{\mathrm{CE}} \geq 1.6$ V.

Moreover, in transistor form, the collector TJ adds (for laser operation) a new dimension to the design and choice of input impedance matching for maximum power transfer. In comparison to the TL, the effective input impedance "looking into" the CE-input port of the TJ-TL is not necessarily large when the BC junction is reverse-biased because the collector TJ provides, in effect, a low-resistance (tunnel) path for current flow ($I_{\mathrm{fk}T}$ and I_{rT}). For the common-emitter TJ-TL (common-collector and common-base configurations are also possible), microwave *S*-parameter measurements yield for the impedance a magnitude of 3–6 Ω for the BE-input port, and 25–30 Ω for the CE-input port. The higher CE-input port impedance is more suited for high frequency signal matching (50 Ω standard) and voltage-controlled modulation. This is a major advantage of the three-terminal TL compared to a two-terminal device, for improvement in signal processing.

Figure 4 shows the modulation characteristics of a common-emitter TJ-TL at two different biases. The biases are chosen so as to maintain the same photon output in each case. A resonance-constrained modulation response with photon-carrier relaxation oscillation at frequency f_R is obtained with the BC junction forward biased in Fig. 4(a). In this mode of operation, the TJ-TL is biased in saturation (i.e., two forward biased *p-n* junctions) as is identified in the regime before the "knee" of the *I-V* characteristics of Fig. 2 and operating in region 1 of Fig. 3. However, when the TJ-TL is operated in the forward-active mode (region 2 of

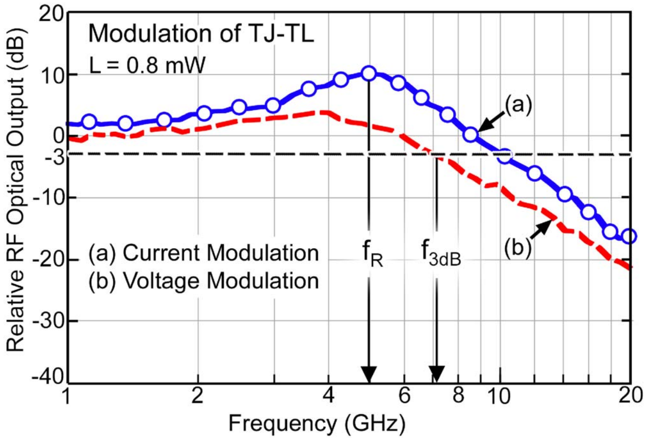

FIG. 4. (Color online) Modulation characteristics of a common-emitter TJ-TL biased in (a) region 1 of Fig. 3 with I_B=90 mA, V_{CE}=0.52 V, and BE rf-input current modulation and (b) region 2 with I_B=90 mA, V_{CE}=1.08 V, and CE rf-input voltage modulation. The optical outputs are equal in both cases.

Fig. 3), the modulation response is absent the resonance, extending the usable bandwidth to the 3 dB bandwidth $f_{3\ \mathrm{dB}}$. The "tilt" in the base charge population, imposed by the boundary condition at the reverse-biased BC junction, removes the (saturated) charge "pile-up" and together with the voltage-controlled photon absorption (FK tunneling) at the collector, contributes to the relatively "flat" response [Fig. 4(b)]. The performance of the TJ-TL employed for the present work is still limited by its large geometry and its prototypical layer structure, resulting in undesirable parasitic delay elements.

Concluding, we have demonstrated a three-terminal TJ TL with a sensitive third terminal voltage control for its optical output. In addition to the usual direct current modulation capability, the collector TJ enables an effective direct voltage-controlled absorption modulation using collector photon-assisted (FK) tunneling.

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